IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Patent Application for:

A METHOD AND APPARATUS FOR TEMPERATURE-CONTROLLED ULTRASONIC INSPECTION

Inventor: James C. P. McKeon, Ph.D.
6422 Osprey Court
Woodbridge, VA 22193

Docket Number: 03-SNX-01

A METHOD AND APPARATUS FOR TEMPERATURE-CONTROLLED ULTRASONIC INSPECTION

PRIORITY CLAIM

This application claims priority from the provisional US patent application titled "Method and Structure for the Efficient Delivery of Sonic Energy to Objects Undergoing SAM Inspection", filed February 19, 2003 and identified by Serial No. 60/448,622, which is hereby incorporated herein by reference.

FIELD OF THE INVENTION

This invention relates generally to the field of ultrasonic inspection. More particularly, this invention relates to an improved method and apparatus for temperature-controlled ultrasonic inspection.

BACKGROUND

Ultrasonic inspection methods, such as Scanning Acoustic Microscopy (SAM), provide valuable tools for the nondestructive inspection of microelectronic components and materials. By analyzing the ultrasonic response from a sample, the different interfaces and features of the sample can be verified. Also, flaws such as delaminations, cracks, voids, die tilt, underfill density variations and solder bump distortions can be detected. Ultrasonic analysis is usually performed by looking for changes in the amplitude or time-of-flight (TOF) of reflections in a high-frequency

waveform signal (A-scan) of the sample at various locations (x, y) in the plane of the sample. By acquiring several A-scans along a line in this plane, a vertical cross-section image can be obtained. Also, by performing a raster-scan over the sample and only recording the amplitude or TOF from a certain depth within the sample at each location (x, y), a horizontal cross-section (C-scan) can be obtained. These images are easier to interpret than the set of A-scans, and are a common method for displaying ultrasonic data. More recently, full 3-dimensional renderings of a sample have become possible by recording the full A-scan at each location (x, y). These data sets allow for simulated scanning for efficient analysis, frequency-domain filtering to enhance of remove desired features, and F-scan imaging to bring out information that may be hidden in the time-domain signal.

All of these inspection methods currently rely upon the use of water to provide acoustic coupling between the ultrasonic transducer and the sample. The coupling may be provided by a flow of water from a dispenser or by immersion of the transducer and sample in a water bath. Typically, in the ultrasonic scanning of microelectronic parts, the water used for acoustic coupling is at ambient room temperature. However, the extent and shape of a flaw in a microelectronic sample may change when the sample is in use because the sample is at an elevated temperature.

The resolution of an ultrasonic scan is largely determined by the wavelength (frequency) of the ultrasound and the focusing ability of the ultrasonic transducer. However, the attenuation of ultrasound in the coupling medium between the transducer and the object being scanned increases rapidly with increasing frequency.

Separations between the transducer and the object being scanned of much less than 0.5mm are currently impractical in scanning acoustic microscopes. This separation sets an effective upper limit on the frequency of the ultrasound and consequently sets a limit on the spatial resolution that may be achieved in the ultrasonic scan.

SUMMARY

The present invention relates generally to improvements in ultrasonic inspection. Objects and features of the invention will become apparent to those of ordinary skill in the art upon consideration of the following detailed description of the invention.

In one embodiment of the invention, the temperature of a coupling medium between an ultrasonic transducer and an object under inspection is maintained at a predetermined temperature so as to facilitate efficient transport of ultrasound. In a further embodiment, the temperature of an object under inspection is maintained at a predetermined temperature so as to simulate the operating environment of the object more closely and facilitate identification of defects or other properties.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as the preferred mode of use, and further objects and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawing(s), wherein:

Figure 1 is a diagrammatic view of an exemplary scanning acoustic microscope in accordance with certain aspects of the present invention.

Figure 2 is a flow chart depicting certain aspects of the method of the invention.

Figure 3 is a flow chart depicting certain aspects of a further method of the invention.

DETAILED DESCRIPTION

While this invention is susceptible of embodiment in many different forms, there is shown in the drawings and will herein be described in detail one or more specific embodiments, with the understanding that the present disclosure is to be considered as exemplary of the principles of the invention and not intended to limit the invention to the specific embodiments shown and described. In the description below, like reference numerals are used to describe the same, similar or corresponding parts in the several views of the drawings.

One aspect of the present invention is a method for improving the efficiency of acoustic coupling between an ultrasonic transducer and an object. Acoustic coupling is usually provided by water. This may be achieved by immersion of the object under inspection (the object to be scanned) and the transducer in a bath of water, by using a dispenser (such as a 'bubbler' or a 'squirter') to create a flow of water between the transducer and the object under inspection or by creating a film of water between the transducer and the object under inspection. Acoustic coupling may also be provided by liquids other than water, by gels, or by solid, elastic materials. The efficiency of the acoustic coupling is determined by how much energy enters the coupling medium, by the attenuation of the acoustic wave within the medium and by the acoustic coupling between the medium and the object.

The attenuation of ultrasonic energy in a coupling medium between an ultrasonic transducer and an object under inspection is modeled by the factor $e^{-2\alpha x}$, where x is the distance traveled by the ultrasound within the coupling medium and α is an attenuation coefficient. To a good approximation, the value of attenuation

coefficient increases with the square of the frequency and depends upon the physical properties of the coupling medium. Thus, it can be seen that to reduce attenuation, either the attenuation coefficient α or the propagation distance x (or both) should be reduced. Separations between the transducer and the object being scanned of much less than 0.5mm are currently impractical in scanning acoustic microscopes. One aspect of the present invention is a method for reducing the attenuation coefficient, α. Such a reduction allows for higher frequencies to be used (resulting in higher resolution) or for larger separations to be used. When the attenuation coefficient is reduced, the energy is transported more efficiently through the coupling medium.

Separations greater than 0.5 mm are typically preferred by users. Also, if the sample under inspection has packages placed close to objects of different heights (as on a populated circuit board), then a greater separation allows the transducer to pass over the other objects to get to the next package of interest. Additionally, an inspection area may be recessed into a sample (such as an optoelectronics device). A longer focal length is then required to avoid the transducer hitting the sides of the recessed area.

A diagrammatic view of an exemplary scanning acoustic microscope 100 of the invention is shown in **Figure 1**. An ultrasonic transducer 102 is coupled to an ultrasonic receiver/pulse unit 104, which in turn is coupled to a computer 106. The computer 106 is used for control of the system and for the analysis, storage and display of ultrasonic data.

In one embodiment, a water heater 108 is used to heat water 110 in a reservoir or water bath 112. A temperature sensor 114 is used to measure the temperature of

the water. The output 116 from the temperature sensor 114 is used by a temperature control mechanism (which may be implemented by the computer 106 or by a separate controller) to control the operation of the water heater 108 via control signal 118. The combination of the heater, sensor and control mechanism form a temperature controller for the coupling medium. In one embodiment, the temperature sensor 114 is a type K thermocouple probe and the water heater 108 is cartridge heater turned on and off by use of a relay controlled by the control signal. A water circulator 120 may be used to ensure an even temperature throughout the reservoir. The water circulator 120 may be integrated with the heater 108. The water heater may be positioned within the reservoir, as shown in Figure 1, or positioned in a tube or pipe carrying water for recirculation.

The temperature sensor 114 may also be used to indicate if the water is over-temperature, and to trigger an emergency stop of the system. The emergency stop may switch the heater off or disconnect electrical power from the system. This prevents damage if, for example, the heater control mechanism fails.

In the embodiment shown in Figure 1, the level of water 110 in the reservoir 112 is controlled by action of a water pump 122 that adds water to the reservoir when the water level, as measured by one or more level indicators 124, is below a predetermined level. Also, a level sensor 126 may be used to indicate over-filling of the reservoir and to trigger an emergency stop of the system. The emergency stop may disconnect electrical power from the system, for example. This prevents damage if, for example, the control mechanism of the water pump fails. The combination of the water pump, level sensors and control mechanism form a water level controller.

The object under inspection 130 is held in an object holder 132. For example, when the object under inspection is a semiconductor wafer, the object holder is typically a wafer chuck, such as a vacuum chuck, that is controlled to immerse the wafer in the reservoir of water. The wafer may be positioned on the chuck manually or by use of a robot arm.

The relative positions of the object under inspection 130 and the ultrasonic transducer 102 are adjusted along a scan-line by action of a first position controller 134 (such as linear-motor or a stepper-motor under control of the system computer 106) that moves the transducer along a track 136. The scan-line is horizontal in Figure 1. A second position controller (not shown) adjusts the relative positions of the object under inspection 130 and the ultrasonic transducer 102 along a step-axis from one scan-line to the next. The scan-line may be a straight line or curved line. A third position controller 138 is used to adjust the distance of the ultrasonic transducer 102 from the object under inspection 130 along a focus-axis to facilitate focusing of the ultrasound to different depths within the object under inspection 130. The focus-axis is vertical in Figure 1. The combination of the first, second and third position controllers form a transducer-position controller.

In an alternative embodiment, the ultrasonic inspection system allows the transducer to be moved about up to 6 axes so as to allow for the inspection of objects with more complicated geometries or to allow for variation of the angle of the transducer relative to the surface of the object. For example, the orientation of the transducer may be changed as the transducer is moved across the curved surface of an object. An example of such a system is a non-destructive testing system for the

inspection of very small parts or surface coatings with very high frequency ultrasound. The ultrasonic inspection system may use one or more transducers to generate ultrasound in the object and may use one or more transducers to sense the ultrasound emitted from the object.

A second temperature sensor 140 may be used to measure the temperature of the object under inspection 130. A second heater 142 may also be used to heat the object under inspection 130. The second heater provides more rapid heating of the object under inspection than is obtained by just immersing the object in the water reservoir. It also provides for temperature control when the object under inspection is not immersed in the water. For example, when the acoustic coupling between the ultrasonic transducer and the object under inspection is provided by a flow of water from a dispenser, the object may have a steady-state temperature below that of the water. The second heater 142 may be incorporated into the object holder 132. The combination of the second heater, second temperature sensor and associated control mechanism form an object-temperature controller. When the object under test is a microelectronic device, it may be desirable to raise the temperature of the device to a temperature representative of an operating temperature of the device before the ultrasonic scan is performed.

In a further embodiment, the acoustic coupling medium is a solid medium that is held at an elevated temperature through surface heating.

In an implementation of a system of the present invention, a Scanning Acoustic Microscope was used to make A-scans and C-scans of a flip-chip sample. The part was placed in a bath of water and scans were made at various temperatures.

The water provided the coupling medium. An ultra-high frequency transducer was used to generate an ultrasonic pulse and sense the ultrasonic pulse reflected from the part. At the ambient temperature (18°C), the center frequency of the reflected pulse was 128.9 MHz. When the temperature of water increased, the attenuation decreased, yielding an increased in the strength of the reflected signal. Since the decrease in attenuation was higher at higher frequencies, the center frequency of the reflected pulse was shifted upwards in frequency. This provided improved resolution in the C-scan image of the microelectronic part. The speed of sound in the water also increased. The results are summarized in Table 1.

Temp. (°C)	Sound speed (mm/μsec)	Change in Center Frequency (MHz)	Water Path Length (mm)	Change in Signal Strength
18	1.483	0	3.1	0 dB
28	1.83	16.6	3.95	6 dB
38	1.879	29.3	4.0	10 dB
48	1.9	32.23	4.1	12 dB

Table 1.

In table 1, the water path length denotes the 'round-trip' water path length. In tests using lower frequency ultrasound, the measured increase in the sound speed was not as great. Also, standard measurements of the sound speed in pure water (at lower frequencies) do not show such a large increase. The reason for the extra increase has not been identified, but may be due to the use of drinking water rather than pure water in the water bath or to other changes within the system that appeared as a sound speed change.

Figure 2 is a flow chart depicting certain aspects of the method of the invention. Referring to **Figure 2**, the method begins at start block 202. At decision

block 204, a check is made to determine if the temperature of the coupling medium (the couplant) is within the predetermined temperature range. If the temperature of the coupling medium is outside of the predetermined temperature range, as depicted by the negative branch from decision block 204, the temperature of the coupling medium is adjusted at block 206. For example, if the temperature is too low, a heater is operated to raise the temperature, if the temperature is too high the coupling medium is allowed to cool. If the coupling medium is a liquid, cooler liquid may be added. If the temperature of the coupling medium is within the predetermined range, as depicted by the positive branch from decision block 204, flow continues to decision block 208.

At decision block 208, a check is made to determine if the temperature of the object under inspection is within the predetermined temperature range. If the temperature of the object under inspection is outside of the predetermined temperature range, as depicted by the negative branch from decision block 208, the temperature of the object under inspection is adjusted at block 210. For example, if the temperature is too low, a heater is operated to raise the temperature, if the temperature is too high the heater is switched off and the object is allowed to cool. If the temperature of the object under inspection is within the predetermined range, as depicted by the positive branch from decision block 208, flow continues to block 212. At block 212, the transducer is operated. If the system is a passive system, the transducer is activated to sense ultrasonic acoustic emissions from the object under inspection. For example, stresses may be applied to the object at this time to induce acoustic emissions. If the system is an active system, the transducer is activated to generate an ultrasonic pulse

that propagates through the coupling medium and impinges on the object under inspection. The ultrasound reflected from or transmitted through the object under inspection is then sensed (either by the same transducer or an additional transducer). At decision block 214 a check is performed to determine if the object under inspection is to be scanned at additional scan points. If not, as depicted by the negative branch from decision block 214, the process terminates at block 216. If more points are to be scanned, as depicted by the positive branch from decision block 214, the scan position is adjusted at block 218, and flow continues to decision block 204. The scan position may be adjusted by moving the transducer, the object or both under the control of a scan controller (implemented by a computer for example). It will be apparent to those of ordinary skill in the art that temperature control of the coupling medium and/or the object may be performed by separate control systems that transmit signals to the scan controller to indicate if the corresponding temperature is within its predetermined range.

Figure 3 is a flow chart depicting an exemplary method for selecting the temperature of the coupling medium. Referring to **Figure 3**, following start block 302, a temperature is selected from a list of temperatures. Preferably, the list of temperatures includes temperatures greater than the ambient temperature and less than the maximum operating temperature of the transducer. For example, the list may contain temperatures in the range 30°C - 50°C. At decision block 306 a check is made to determine if the temperature of the coupling medium (couplant) is within the predetermined temperature range. If the temperature of the coupling medium is outside of the predetermined temperature range, as depicted by the negative branch

from decision block 306, the temperature of the coupling medium is adjusted at block 308. For example, if the temperature is too low, a heater is operated to raise the temperature, if the temperature is too high, the coupling medium is allowed to cool. For example, cooler water may be added when the coupling medium is water. If the temperature of the coupling medium is within the predetermined range, as depicted by the positive branch from decision block 306, flow continues to block 309 where, optionally, the acoustic path length is adjusted as necessary as the temperature is changed (so as to adjust signal strength or focus, for example). Flow continues to block 310, where the attenuation of the coupling medium is determined. This may be done, for example, by measuring the strength of an ultrasonic pulse with a fixed- or known-amplitude. At decision block 312, a check is made to determine if more temperatures are to be measured. If more temperatures are to be measured, as determined by the positive branch from decision block 312, flow returns to block 304 and the next temperature is selected from the list of temperatures. If no more temperatures are to be measured, as determined by the negative branch from decision block 312, the best temperature is selected based upon the attenuation at each temperature and other relevant factors. For example, if the lowest attenuation is achieved at a temperature close to the maximum permitted for the transducer, a slightly lower temperature may be selected. The process terminates at block 316.

The attenuation coefficient for a liquid is approximated by the expression

$$\alpha = \frac{\omega^2}{2\rho_0 c^3}\left(\tfrac{4}{3}\eta + \eta_B\right),$$

where ω, ρ_0 and c, respectively, are the radian frequency of the ultrasonic wave, the density of the liquid and the sound speed of the liquid, η is the of shear viscosity and η_B is bulk coefficient of viscosity. In general, the viscosities and the density decrease with increasing temperature, while the sound speed first increases and then decreases. The net result, as confirmed by experimentation, is a decreasing in attenuation with temperature. At lower frequencies the decrease in attenuation is small. However at very high frequencies the decrease in attenuation is significant, as described above.

The acoustic impedance of the coupling medium is also temperature dependent. The relationship between the impedance of the coupling medium and that of the transducer influence the ability of the transducer to couple acoustic energy into the coupling medium. As a result, the temperature selected for operation may also depend upon the properties of the ultrasonic transducer. For example, an ultrasonic transducer lens made of fused silica has a density = .0022 g/mm^3 and a compressional sound speed c_L = 5.95 mm/μs, so its characteristic acoustic impedance is Z_L = 13.09 x 10^{-3} g /(mm^2 μs). Water at 18°C has a density = .00099868 g/mm^3, and a sound speed c = 1.483 mm/μs, giving a specific acoustic impedance Z_W = 1.481 x 10^{-3} g/(mm^2 μs). Water at 48°C has a density = .00098892 g/mm^3, and the sound speed was measured at ultrahigh frequency to be c = 1.9 mm/μs, giving a specific acoustic impedance Z_W = 1.879 x 10^{-3} g/(mm^2 μs). The pressure transmission coefficient from the lens of the transducer to the coupling water is related to the impedances by $T=2Z_W/(Z_L+Z_W)$, so at 18°C, T=0.2, whereas at 48°C, T=0.25. This represents a 2dB increase in signal strength.

The intensity transmission coefficient between the lens and the water (in either direction) is $T_I = 4Z_W Z_L / (Z_L+Z_W)^2$. At 18°C, $T_I=0.35$, whereas at 48°C, $T_I=0.422$. This represents a 1.62dB increase in the energy returned to the transducer due to the improved impedance matching. Thus the overall improvement in signal gain is due to the reduction in attenuation and the improved impedance matching.

These improvements are achieved because the impedance of the heated water is more closely matched to the impedance of the transducer lens. Similarly, the transmission coefficient between the coupling medium and the object under inspection may be enhanced by changing the impedance of the coupling medium to better match that of the object. This allows more ultrasonic energy to enter the object under test and more energy to be returned from the object under test to the coupling medium.

While the invention has been described in conjunction with specific embodiments, it is evident that many alternatives, modifications, permutations and variations will become apparent to those of ordinary skill in the art in light of the foregoing description. Accordingly, it is intended that the present invention embrace all such alternatives, modifications and variations as fall within the scope of the appended claims.

What is claimed is: